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RESEARCH MEMORANDUM

A PRELIMINARY INVESTIGATION OF HIGH-SPEED IMPACT: THE PENETRATION OF SMALL SPHERES INTO THICK COPPER TARGETS

By A. C. Charters and G. S. Locke, Jr.

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Declassified by Authority of LARC Security Classification officer (SCO) Letter dated June 16 1983

Maurice F. Bowman

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RESEARCH MEMORANDUM

A PRELIMINARY INVESTIGATION OF HIGH-SPEED IMPACT:

THE PENETRATION OF SMALL SPHERES

INTO THICK COPPER TARGETS

By A. C. Charters and G. S. Locke, Jr.

SUMMARY

Experiments on high-speed impact have been carried out by firing small spheres of different materials into thick plates of lead and copper. The tests have shown that the craters in the two metals had similar shapes and that the penetrations were nearly the same at the same impact Mach number, defined as the ratio of the velocity of impact to the speed of sound in the target metal. Since lead has a low speed of sound compared to copper, the results of impact in lead at moderate speeds have made it possible to predict the effects of impact in copper at very high speeds.

One particularly noteworthy result came from a series of tests in which the material of the sphere was varied but the mass of the sphere was held constant by changing its diameter. This series demonstrated that the denser materials produced greater penetrations in actual depths despite their smaller sizes.

In general, it was found that all of the penetrations produced by spherical projectiles could be correlated quite well for engineering purposes by a function relating the depth of penetration to the impact momentum per unit volume.

INTRODUCTION

The skin of an aircraft is the outermost barrier protecting the interior from exposure to the elements. The air stream and solar radiation beat continually on the aircraft, and, at times the skin must protect against the impact of denser media, such as rain, dust, or even hail. However, this function of the skin as a protective shield is usually secondary to its functions as a contoured aerodynamic surface and as part of the load-bearing structure. Normally the outer skin is designed by aerodynamic and structural requirements, and the protection which may be needed against external cooling (or heating) and so forth is provided by adding an inner skin of insulation.

The role of the outer skin as a protective shield takes on a new significance for certain classes of very high-speed vehicles. One example is the earth satellite. This vehicle will be showered with small meteoroids as it orbits about the earth and the outer skin must be strong enough to withstand their bombardment. Consequently, the design of vehicles of this class must take into account the ability of the outer skin to withstand damage done by impact of meteoric particles as well as aerodynamic and structural requirements.

If one takes the broad view, the impact of small particles at high speeds is a new facet of aeronautics that appears as flight speeds are increased to hypersonic values. Specifically, the designer will be concerned with particles ranging in size from a few mils to an inch or so. Their shape may or may not be regular but their dimensions in three perpendicular directions will be roughly the same. Their composition may vary widely, all the way from light stony materials to heavy metal objects. The velocities of impact may run from 10,000 to 30,000 feet per second and above. These are roughly the boundaries defining the region of interest to aeronautics.

The state of knowledge within these boundaries is far from satisfactory from the standpoint of either theory or experiment. The theory has yet to propose a physical model of the impact process that is in full agreement with the observations. The experimental data are quite limited in extent, and many of the tests are handicapped because the conditions of the experiment could not be controlled or measured with precision. For example, if it is required that the heat shield of a long-range missile provide protection from stony meteoroids a fraction of an inch in diameter, the thickness of the shield could not be estimated with any real confidence in the result.

A program of research in high-speed impact carried out at the Ames Aeronautical Laboratory has consisted of firing small spheres at thick copper plates, since it is believed that impacts of this type might occur during the flight of an intercontinental ballistic missile. Thus, the tests have been focused on a situation of particular interest at the present time. The preliminary phase of the investigation is now complete, and results are available for predicting the penetration of spheres into copper targets at ICBM re-entry velocities.

SYMBOLS

- c speed of sound in target material, ft/sec
- d diameter of sphere, in.
- m mass of sphere, grams
- p penetration: depth of cavity, measured from original surface of target, in.
- V velocity of sphere at impact, ft/sec
- ρ_P density of sphere, lb/cu in.
- ρ_T density of target material, lb/cu in.

EXPERIMENTAL PROCEDURE

The apparatus used in the impact tests is shown schematically in figure 1. The spheres were fired from the gun at the left, traversed several chambers (vented to the room), and impacted the target at the right.

Both a powder gun and a piston-compression light-gas gun were used. The caliber in both cases was a little less than 1/4 inch. The spheres were fired in a sabot, the design of which is indicated in the sketch inserted at the lower left of the figure. The sabot imparted the force of the propellant gas to the sphere and guided it down the gun tube during the firing while protecting it from erosion from the gases or from rubbing against the surface of the tube. The sabots were made of nylon and consisted of two halves, as shown in the sketch. Their manufacture was quite simple: They were turned as a cylinder and split into two parts with a knife. The halves stayed together as a unit in the barrel but were separated on leaving the muzzle, first by the blast of gas pouring out of the gun and later by the action of the air. The separation of the halves increased as they traversed the blast tank and this permitted them to be trapped in the tank. The diameter of the exit port was large enough to give free access to the sphere but was less than the separation distance between the halves of the sabot at this point in their flight. As a result, the sphere alone traversed the remaining chambers and struck the target, thus freeing the impact tests from any complicating effects of the sabots.

Two spark photographs were taken of the sphere as it traversed the velocity chamber. Now, a simple spark station with the light from the spark casting a shadow directly on the photographic film is not suitable at this location just downrange from the blast tank because extraneous light from the muzzle blast and from the luminous gases surrounding the sphere at high speeds of flight tends to fog the film and obscure the sphere's shadow. It is necessary to use an optical system which discriminates against the extraneous light, and this purpose is accomplished by the use of schlieren-type spark stations which are shown schematically in figure 1. The light from the spark is focused on a small hole in a diaphragm placed just in front of the camera lens, while the camera itself is focused on the trajectory. The diameter of the hole is several times larger than the effective diameter of the spark but is small compared to the focal length of the lens, so that the ratio of the focal length to hole diameter is about 70. Consequently, the total light output of the spark enters the camera just as though the diaphragm were not there, but only a fraction of the extraneous light can reach the film through the small aperture.

A print of a typical spark photograph is inserted in the lower right-hand corner of figure 1. The sphere itself is silhouetted sharply since the camera is focused on the trajectory; however, enough schlieren effect is produced by the hole in the diaphragm to give an outline of the head wave. Another feature to be noticed is the silhouette of each reference marker, which is seen as a point projecting into the top or the bottom side of the picture. These markers serve to locate the sphere along its trajectory at the instant the spark photograph is taken.

The time from one spark photograph to the next is recorded on a cycle-counter chronograph. The distances from one marker to the next and to the target are measured. The sphere is weighed and its diameter measured before firing. It is assumed that the drag coefficient of a sphere, C_D, has a constant value of 0.80.[1] These data are used to compute the velocity of the sphere as it strikes the target. The measurements of time and distance are quite accurate (1 microsecond and 0.01 inch, respectively) and it is believed that the velocities are correct to 0.1 percent. It should be mentioned that each spark station is triggered by a photobeam placed just uprange of the station. The time signal, however, comes directly from the discharge of the main spark itself.

In addition to determining the velocity of impact, the spark photos give a clear record of the condition of the sphere in flight. They show whether the sphere was damaged by firing and whether the halves of the sabot were cleanly separated and contained in the blast tank. Consequently, the apparatus enables the observer to state with confidence that the impact phenomena are due solely to a sphere striking the target at a known speed and as a sound structural unit.

The targets were mounted on a rigid framework some 6 feet downrange from the gun muzzle. Actually, this was the most convenient location

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[1]A better value of C_D for spheres at Mach numbers of 5 and above is 0.91. However, the results given in this report are not affected appreciably by this change.

close to the gun, but it should be mentioned that all of the muzzle blast had been filtered out by the chambers between this location and the muzzle. Consequently, the tests are free from this disturbance as well as from the pieces of the sabot.

The lateral dimensions of the targets were 4 by 4 inches, and the thickness for all targets was 1 inch at the lower velocities and 2 inches at the higher velocities. Since the largest cavity produced in the present series of tests was roughly a hemisphere with a 1/2-inch radius, it can be seen that the size of the target was massive compared to the cavity, and it is believed that the target plates behaved as semi-infinite solids. This assertion was borne out by observation of the targets before and after impact, which showed that the side and back surfaces were not deformed.

The interest in these preliminary tests was focused on the depth of penetration, and the only quantity measured on all targets was the depth of the cavity. This measurement was made from undisturbed front face of the target plate to the deepest place in the cavity. There were no ambiguities involved because the surfaces of the cavities were smooth and regular, being roughly hemispherical in shape, and the surface of the plate was distorted only in the immediate neighborhood of the cavity. In practice, the depth was measured by a depth micrometer from the surface of two parallel bars placed on the face of the target down to the top of a small ball which had been dropped in the bottom of the cavity.

In a few of the tests some additional measurements were made in order to shed light on the physical nature of the impact process. Contours of the cavities were obtained from castings. Some of the plates were weighed before and after impact to determine the loss of metal, and in these tests a hollow wood cylinder, labeled "fragment tube" in figure 1, was placed in front of the target coaxial with the expected point of impact. It was found that some metal was thrown back from the face of the target in a conical spray, like water from a garden hose nozzle, and the fragment tube served to collect the particles in this spray.

The scope of the research covered in this report is summarized as follows:

The projectiles were spheres having a constant diameter of 1/8 inch, except in one series of tests in which the mass was held constant and the diameter was varied accordingly. The materials of all spheres were metals, but the composition was varied from a light magnesium-lithium alloy on the one hand to a heavy, sintered tungsten compound on the other.

The targets were all massive compared to the cavities and it is believed that they were, in effect, semi-infinite solids. In all tests the surface of the target was oriented perpendicular to the trajectory. In other words, only "normal" impact (in contrast to oblique impact) was investigated in these preliminary tests. Only one material, copper, was of direct interest, although two materials, copper and lead, were tested. Lead was included as a target material because certain theoretical considerations suggest that the cavities produced in lead at low speed are very similar to those produced in copper at high speed. Consequently, it is possible to obtain information about very high-speed impact in copper from firings into lead at relatively moderate speeds, which were within the capacity of the guns available at the time of these experiments.

The velocities of impact were varied from 1,000 to 10,000 ft/sec. However, the analysis of data from these tests and from experiments carried out elsewhere suggests that the results can be correlated on the basis of a pseudo Mach number, the ratio of the velocity of impact to the speed of sound in the target material. This impact Mach number was varied from 0.4 to 0.9 for the firings into copper targets and from 0.3 to 1.8 for the firings into lead targets. Consequently, firings into lead simulated firings into copper over the range of velocities from 3,500 to 21,000 ft/sec, although the firings into copper itself covered the range from only 4,400 to 10,000 ft/sec.

RESULTS AND DISCUSSION

The primary purpose of the impact program was to obtain information on the depth of penetration. The number of tests was not sufficient for any general conclusions to be drawn about the physical processes which occur during impact, but it may be instructive to make a few observations concerning the formation of the cavities.

Comments on the Impact Process

A representative cavity is shown in figure 2. A photograph of the target face is shown at the top of the figure. The target block was sectioned, and a photograph of the section is shown at the bottom of the figure. The artist has also sketched in the sphere, the outline of the fragment tube, and the spray of the metal thrown from the target. These additional features are drawn to scale. The target in question is a lead plate struck by a 1/8-inch-diameter lead sphere at 7,000 ft/sec.

It should be noted that the size of the cavity is very large compared to that of the sphere, as mentioned previously. This observation reflects the fact that high-speed impact is a process of great violence. Even at the relatively low velocity of 10,000 ft/sec the kinetic energy of the sphere is 2,000 Btu per pound, which is comparable to the potential energy of nitroglycerine (2,750 Btu/lb). There is ample energy to completely vaporize a lead sphere since only 1,660 Btu/lb are required, but one should not conclude that the energy is expended this way. In fact, the Ames tests indicate that little if any material is vaporized.

The energy appears to go into a plastic flow of sphere and target material which results in the formation of the cavity. The results of the experiments suggest that the cavity is produced by a hydraulic mining process similar to that proposed for shaped charge penetration (ref. 1). This contention is borne out by the following observations:

First, relatively little material was lost from the target as a result of the impact, if one considers the weight of target material filling the cavity as the basis for comparison. The weighings before and after showed that only a quarter of this weight was lost from the target block. Also, all of the material thrown out was contained in the side spray which was composed of small particles of various sizes but little if any vapor. Consequently, a negligible quantity of material could have been vaporized because the total weight of sphere and target block was accounted for and there was no evidence of any vapors being deposited in the fragment tube.

Second, the surface of the cavity is coated with the material of the sphere. This coating makes a striking appearance when the metals of the sphere and target have a different color (e.g., when the sphere is lead and the target is copper, as shown in fig. 3). The entire surface of the cavity is covered with a smooth, silver colored coat of lead which contrasts with the red color of the copper block. Now, if the metals of the sphere and target flowed like liquids during the impact process, the formation of the cavity would be completed with the metal of the sphere having flowed out into a thin coating over the outside surface of the cavity, which is observed to be the case. Consequently, the hydraulic analogy of shaped charge penetration would appear to explain the formation of cavities in the present impact tests also.

Lead is a ductile metal, of course, and it might be expected to behave like a liquid under the action of very great forces. However, the same process takes place even though the material of the sphere is a hard, brittle metal. This is illustrated in figure 4 which shows the cavity produced by a high-carbon steel ball impacting a copper target. The steel sphere does not flow smoothly as lead does but rather fragments into many small pieces which float on top of the flow of target metal during the formation of the cavity as though they were pieces of ice floating on a river. They come to rest adhering to the surface of the cavity, so that the over-all result is the same as for a lead sphere; namely, the material of the sphere coats the surface of the cavity. The fragmentation of the steel ball is to be expected, of course, if one computes the dynamic pressure in the steel due to the velocity of impact, $(\rho_T V^2)/2$. Even at

7,000 ft/sec the dynamic pressure exceeds 2×10^6 pounds per square inch and, consequently, is some ten times the ultimate strength of the steel.

The Use of Lead as a Target Material to Simulate High-Speed Impact in Copper

Copper was chosen as the target material of primary interest in these preliminary tests because it has certain properties which may make it suitable for use as the outer skin of a high-speed missile. It was desired to test at velocities of impact which were as high as the greatest flight speeds of these missiles, that is, at velocities of 20,000 ft/sec and above, but the guns which were available at the time of these tests could not fire at these speeds. As a result, a different method was sought for exploring the nature of impact at full flight speeds from firings at the velocities within reach (up to 10,000 ft/sec).

The key to a low-speed analog of high-speed impact is given in an analysis made by J. H. Huth and associates of experiments which were carried out at the University of Utah and the Naval Research Laboratory (ref. 2). Huth found that penetrations into targets of different metals could be correlated on the basis of the speed of sound in the target metal, and suggested that the correct dimensionless parameter was the ratio of the velocity of impact to the speed of sound in the target material. He called this ratio the "impact Mach number." If this hypothesis is correct, impact in lead at low speed will simulate impact in copper at high speed, because the speed of sound in lead, 4,025 ft/sec, is only a third of that in copper, 11,670 ft/sec. Consequently, impact in copper at 20,000 ft/sec could be reproduced by firings into lead at 7,000 ft/sec, a velocity within the capacity of the guns available at the time.

Huth's hypothesis was tested by firing lead spheres into lead targets and copper spheres into copper targets and comparing the results on the basis of the impact Mach number. First, a comparison of the target blocks themselves is shown in figure 5. The lead targets are shown at the top of the slide, and the copper targets at the bottom. The impact Mach number scale is shown in the center. Both sets of targets are arranged in order of increasing Mach number from left to right, with the actual Mach number for each target block marked by a line from the target block to the Mach number scale. The first three targets on the left of both the lead and copper series were selected to compare cavities in the two metals at approximately the same Mach number. The similarity between cavities in lead and copper at the same Mach number is quite evident. In fact, cavities in the two materials are nearly identical at the same Mach number, except for minor details in the vicinity of the lip. Furthermore, the cavities not only look alike, but also the penetrations are the same at the same impact Mach number, as will be discussed shortly.

It should be noted that the impact Mach numbers for copper which correspond to re-entry velocities for an IRBM and an ICBM are indicated on the Mach number scale. Let it be assumed that the impact Mach number gives a correct picture of the impact process. Then, the lead target block at the upper right shows the cavity that would be struck into the copper heat shield of a re-entering long-range missile by a stationary 1/8-inch copper sphere (displayed in the lower right-hand corner of fig. 5).

Dependence of Penetration on Impact Mach Number

The impact program consisted of two parts. In the first part, the size and material of the sphere were held constant and the velocity was varied. In the second part, the velocity and weight of the sphere were held constant and the material was varied. These two parts will be discussed in this order and then a formula will be presented which was found to correlate all of the penetration data.

In the first part lead spheres were fired against lead targets and copper spheres against copper targets. All spheres had a diameter of 1/8 inch. A selection of representative cavities has already been shown in figure 5.

The quantitative results are shown in the graph of figure 6, a log-log plot of penetration versus impact Mach number. The dimensions of the physical quantities involved are shown in the sketch in the upper right-hand corner. Handbook values were used for the speed of sound in the target metal, c, namely, 4,025 ft/sec for lead and 11,670 ft/sec for copper.

The graph shows that the data for lead and copper are correlated fairly well by the impact Mach number. Actually, the differences between the two sets of data are a little greater than can be explained by experimental scatter. For engineering purposes the correlation is believed to be satisfactory, and all of the points can be represented by a single curve. It was found that the data could be fitted by a straight line and, since the plot is log-log, a linear variation indicates that the penetration varies with a power of the Mach number. The significance of this point will be discussed later.

In the second part of the program the tests were planned to provide an answer to the question: "How does the penetration vary when the densities of sphere and target differ?" The spheres were made from different metals ranging from a light, magnesium-lithium alloy, on the one hand, to a heavy, sintered tungsten compound on the other. The weights of all spheres were held constant at 0.130 gram, and their diameters were varied as the densities of their materials required. The velocity was also held constant at 7,000 ft/sec, which was the highest convenient velocity that the guns could be fired (at the time of the tests). Reliance was placed in the use of lead to simulate high-speed impact in copper, and firings were made into both lead and copper targets.

The qualitative results are presented in figure 7.[2] This photograph shows the cavities in lead targets which have been produced by spheres of different materials. The target blocks have been arranged roughly in the order of the densities of the spheres, starting with a magnesium-lithium alloy sphere in the upper left corner, a Duralumin sphere just below it, a steel sphere top center, a copper sphere bottom center, a lead sphere in the top right corner, and a sintered tungsten sphere in the bottom right corner. A sphere of the material concerned is displayed on a plaque alongside the cavity on each target block so that one can compare the sizes of all spheres and cavities at a glance.

The answer to the question previously posed can be seen at once. The largest, deepest cavity is made by the smallest, most dense sphere. In other words, the denser the material of the particle which is struck by the missile, the larger will be the cavity which is formed by the impact.

It might be expected that the density of the sphere material would not be the only factor involved and that the strength of the material would also play a role. However, a few additional tests along this line suggested that strength of the projectile was not a factor under the conditions of impact covered by this investigation and that density alone was the controlling variable. That this should be the case is not too surprising if one recalls a calculation in a preceding section which showed that the dynamic pressures generated during impact at high speed are many, many times greater than the ultimate strengths of all known materials.

The quantitative results of this second part are presented in figure 8 as a log-log plot of the penetration against the density of the sphere. The data from the lead targets cluster about the top line and from the copper targets about the bottom line. The penetrations into lead are much deeper, of course, than those into copper because the impact Mach number in lead is much greater than in copper for the same impact velocity, being 1.7 in lead compared to 0.6 in copper in these tests. This graph bears out the conclusion drawn from the previous slide, namely, that the penetration increases with density. It should be noticed also that both sets of data are fitted satisfactorily by straight lines on this log-log plot.

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[2]In practice, the velocities vary by a few hundred feet per second from round to round. These relatively small differences were accounted for in reducing the data shown in figure 7 by correcting the penetrations to the common velocity of 7000 ft/sec through the use of a 0.69 power law variation of penetration with velocity (see subsequent section on "Correlation of All Impact Data").

Correlation of All Impact Data

The linear variation of the log of the penetration with both the log of the impact Mach number and the log of the sphere's density is a fortunate result insofar as an analysis of the data is concerned, for it suggests that the penetration is a function of a single parameter composed of the product of a power of the Mach number with a power of the density. This, in fact, is the case. The results are shown in figure 9. The parameter in question is the product of the density ratio, ρ_P/ρ_T, with the impact Mach number, V/c, where ρ_P is the density of the sphere and ρ_T is the density of the target. All of the data from these preliminary tests are given on this log-log plot of p/d versus $(\rho_P/\rho_T)(V/c)$, and it can be seen that they are all fitted reasonably well by a straight line, the formula for which is

$$\frac{p}{d} = 2.28\left(\frac{\rho_P}{\rho_T}\right)^{0.69}\left(\frac{V}{c}\right)^{0.69}$$

It should be noted that the derivation of this formula was preceded by an independent analysis of the data from each part of the program in which it was found that p/d varied with the same power of ρ_P/ρ_T as of V/c. Consequently, the two could be combined in a simple product in the complete analysis.

CONCLUDING REMARKS

The ability to correlate all of the data by one formula is certainly convenient and provides an engineering basis for predicting the effects of high-speed impact. If one seeks a physical explanation, this correlation suggests that for a given target the penetration of spheres depends upon their impact momentum per unit volume; that is, upon the product, $(\rho_P V)$.

An additional clue to the physics of impact may be gained if the 0.69 power in the formula is changed to 2/3. Actually, the difference between 0.69 and 2/3 is hardly significant at this stage of the experimentation. If 2/3 is used as the power in the penetration formula and it is assumed that the cavity is a hemisphere with radius p, then cubing both sides of the formula gives, after some rearrangement,

$$\left(\frac{\rho_T c^2}{2}\right)\left(\frac{2}{3}\pi p^3\right) = \text{const}\left(\frac{\rho_P}{\rho_T}\right)\left(\frac{mV^2}{2}\right)$$

The above relation shows that the volume of the cavity is proportional to the product of the density ratio ρ_P/ρ_T with the total kinetic energy of the impacting projectile. Now, the relation between the volume of the cavity and the kinetic energy of the impacting projectile has been proposed elsewhere and has a certain physical appeal, despite the fact that there is some evidence to the contrary. However, the requirement that the kinetic energy must be multiplied by the ratio of the density of the projectile to that of the target is new and its physical significance is an open question at the moment. Whatever its significance proves to be, the penetration formula permits the missile designer to get along with the task in hand, that is, with the design of an outer skin for his missile which will be strong enough to withstand the impact of small particles at high flight speeds.

It should be noted that the penetration formula

$$\frac{p}{d} = 2.28\left(\frac{\rho_P}{\rho_T}\right)^{0.69}\left(\frac{V}{c}\right)^{0.69}$$

stems from a dimensional analysis of impact. It is not derived from a well-established theory of the physics of impact. Consequently, the above formula should be used with this limitation in mind. All of the evidence suggests that the formula predicts reliably the penetration of small metal spheres (and probably, also, nonmetalic spheres) in thick copper and lead targets at high speeds, that is, at values of V/c from 0.5 to 2.0 (and possibly higher) with the target oriented perpendicular to the trajectory. On the other hand, the formula may or may not give the correct penetration if the target is of another material or if its thickness is comparable to the penetration or if its orientation departs very far from the perpendicular. A theory must be developed from considerations of the basic physics of the impact process and the predictions of this theory must be checked by experiments carried out under proper test conditions before a general formula can be written that will cover the full range of impact situations that may occur in high-speed flight.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Feb. 26, 1958

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2. Huth, J. H., Thompson, J. S., and Van Valkenburg, M. E.: Some New Data on High-Speed Impact Phenomena. Jour. Appl. Mech., vol. 24, no. 65, Mar. 1957.

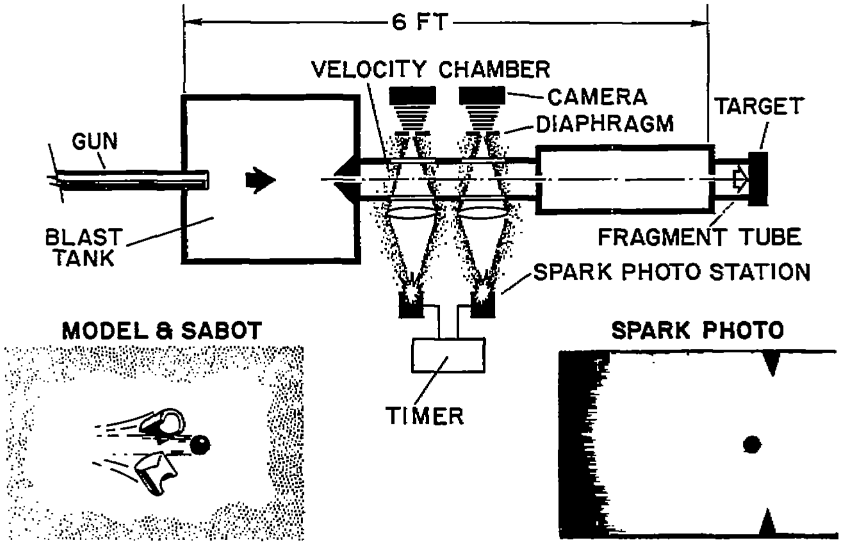

Figure 1.- Test apparatus.

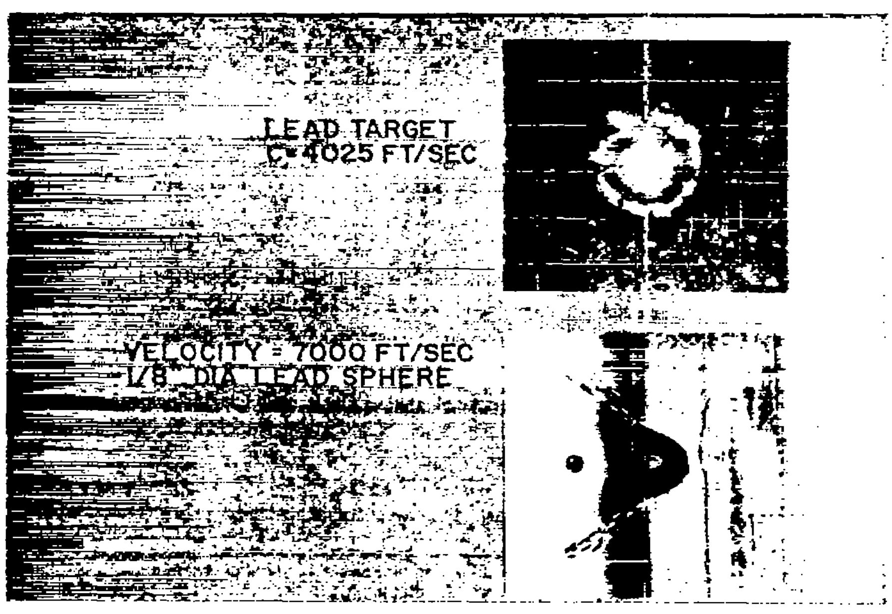

Figure 2:- Cavity formed by high-speed impact of sphere.

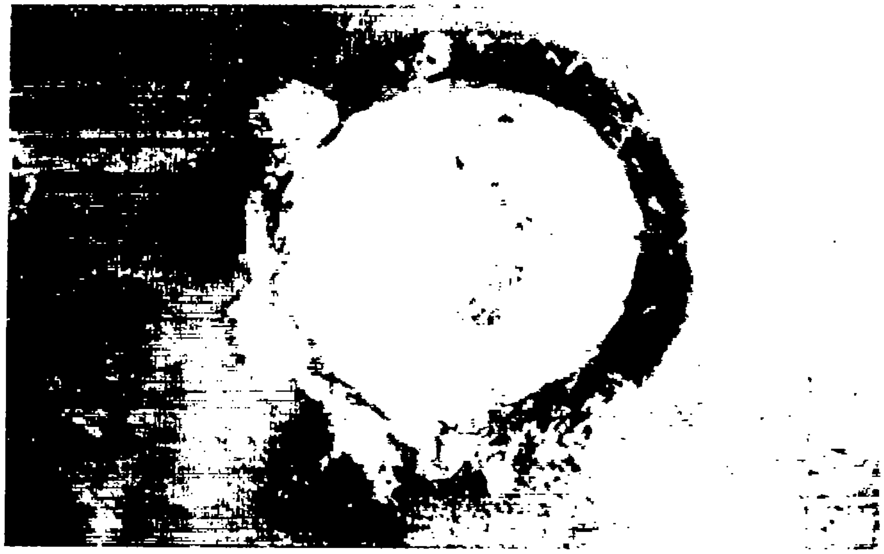

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Figure 3.- Cavity plating from impact of lead sphere on copper target.

A-23162-5

Figure 4.- Cavity plating from impact of steel sphere on copper target.

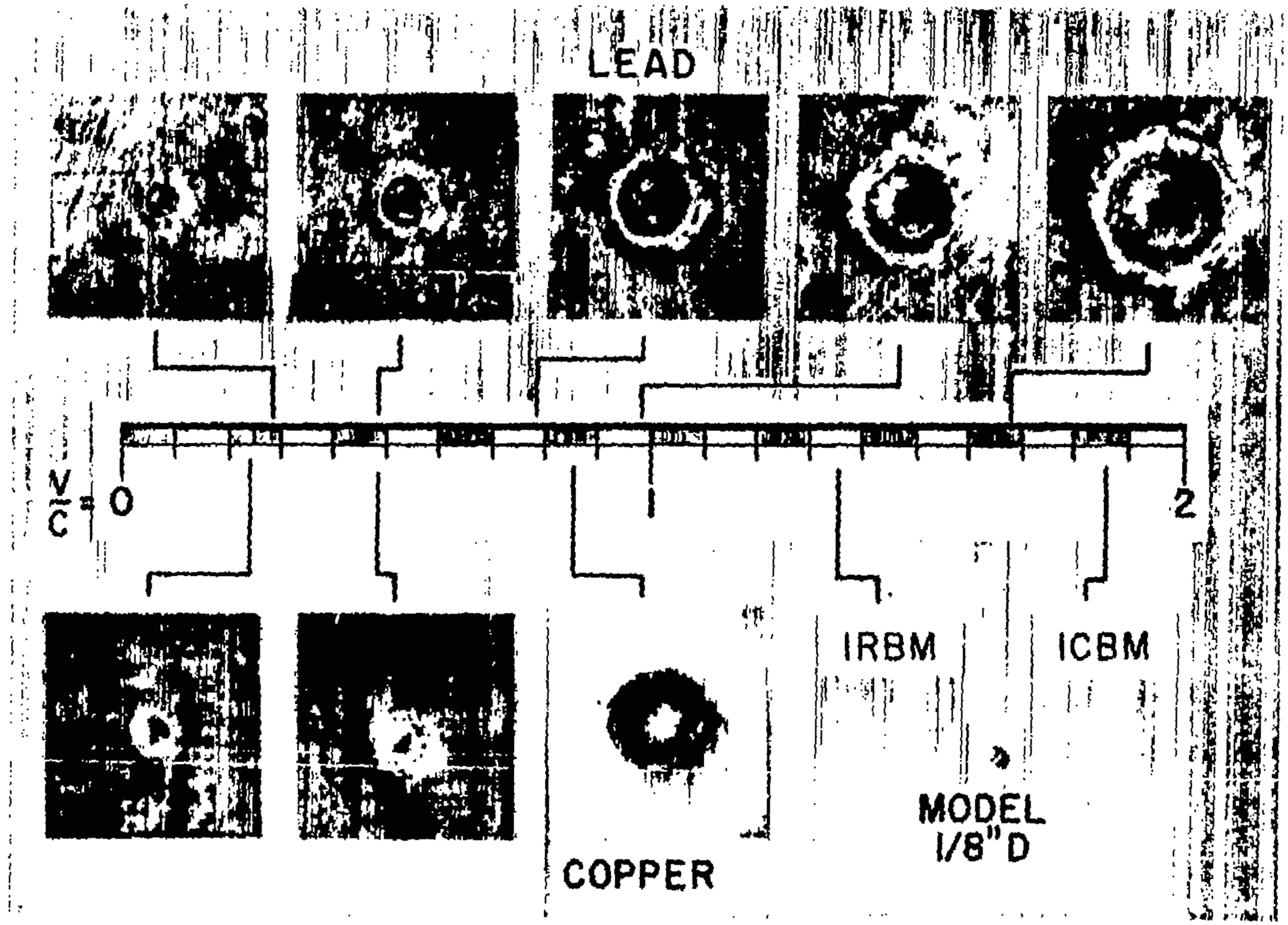

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Figure 5.- Cavities from impacts of lead spheres on lead targets and copper spheres on copper targets.

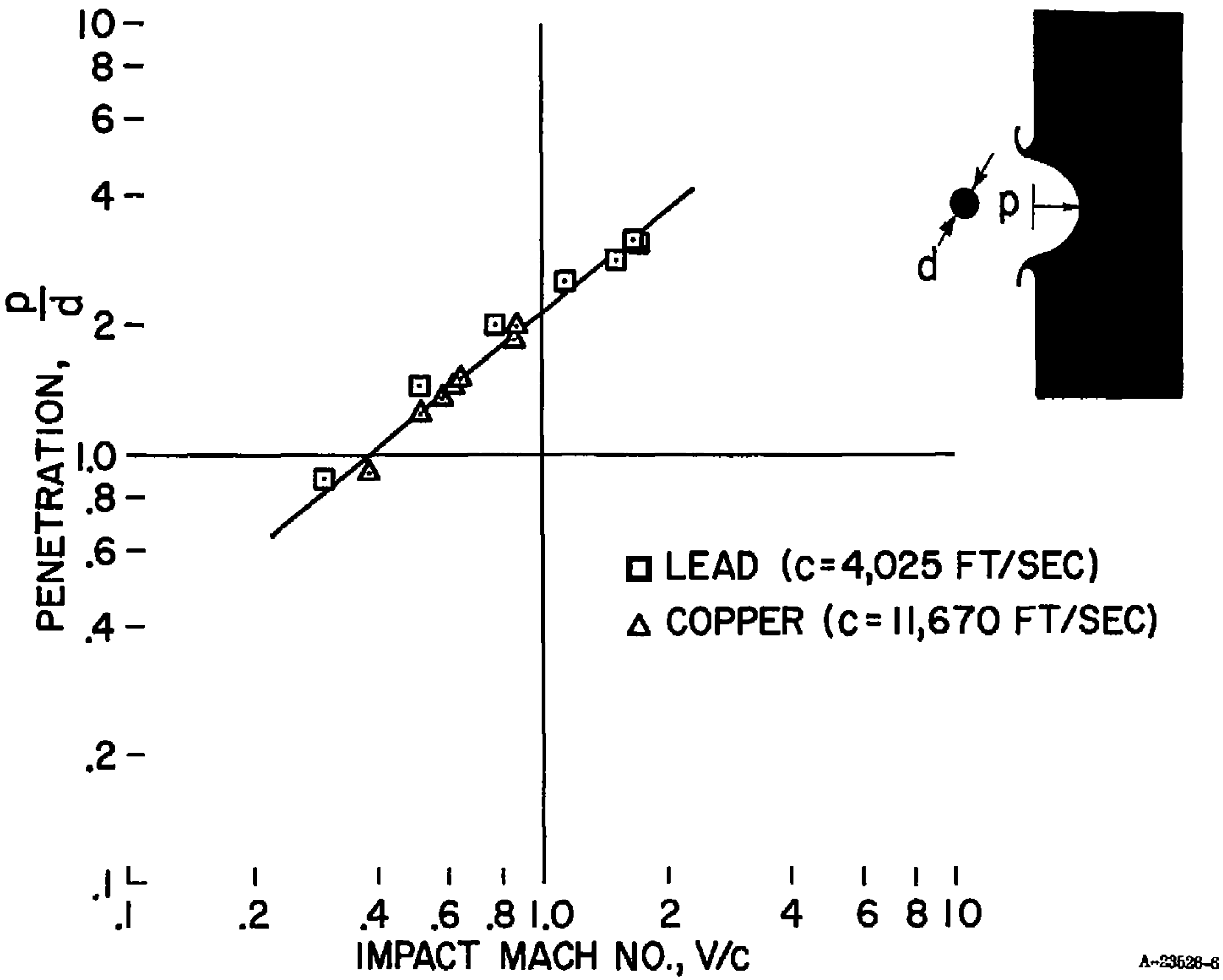
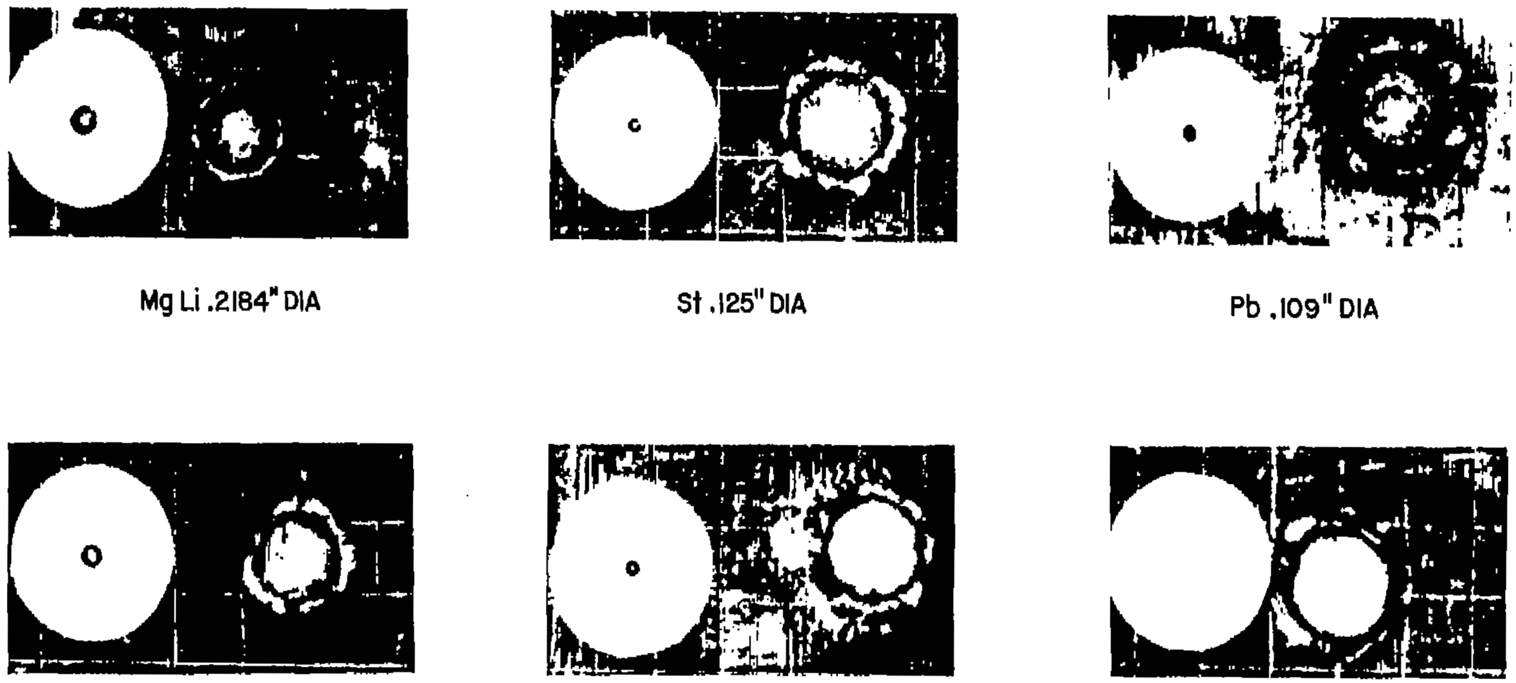


Figure 6.- Penetration vs. impact Mach number for lead spheres on lead targets and copper spheres on copper targets.



CONSTANT VELOCITY 7000'/SEC $\frac{V}{C}=1.74$

EQUIVALENT VELOCITY FOR COPPER 20,300'/SEC

Figure 7.- Cavities in lead targets formed by impact of spheres of different materials but having constant mass and impact velocity.

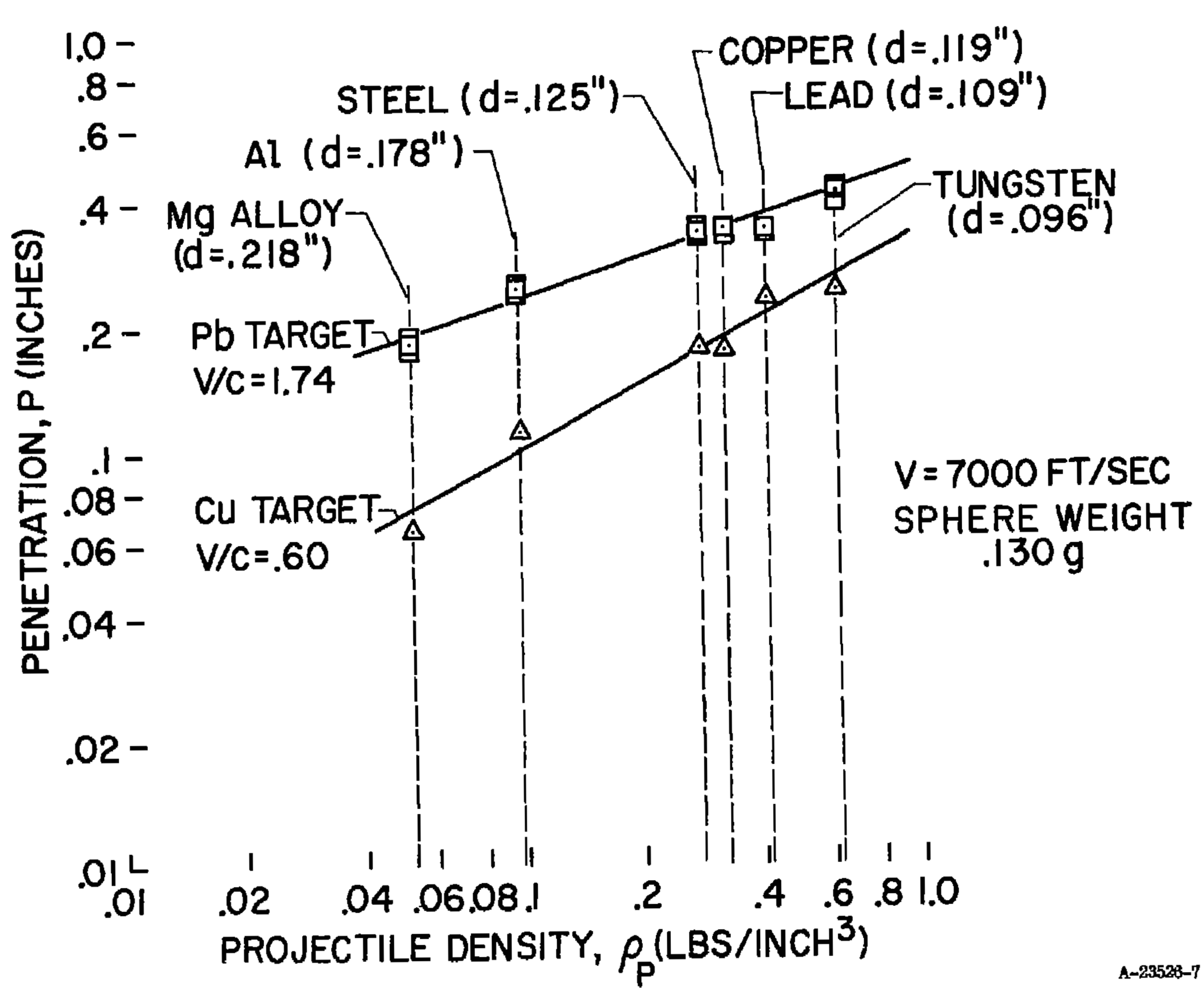


Figure 8.- Penetration vs. density for spheres of different materials but having constant mass and impact velocity.

[redacted]

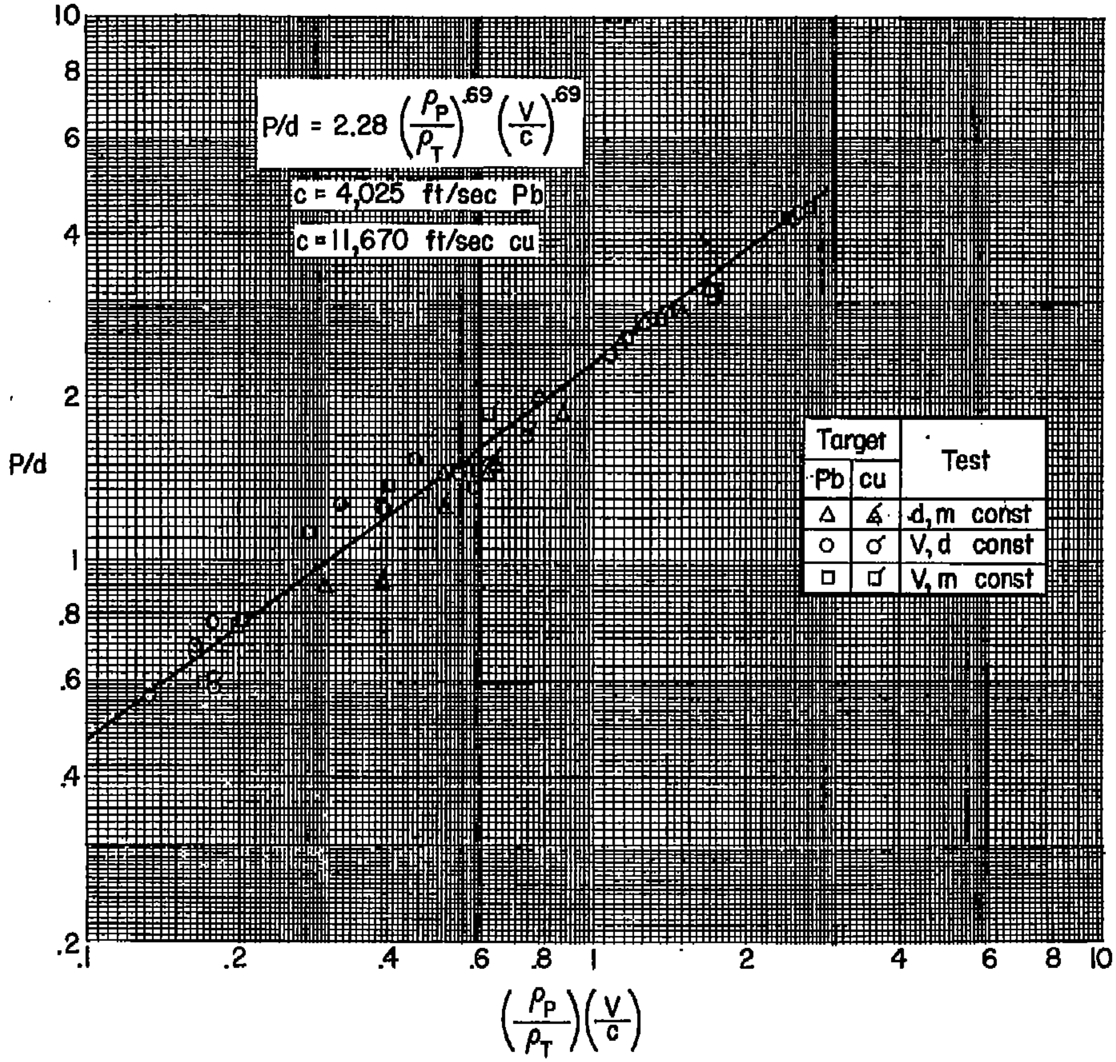


Figure 9.- Penetration vs. impact parameter.

[redacted]

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